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"CARBON ELECTRODE DEVELOPMENT PROGRAM"

CONTRACT NO. NAS 9-3699

FINAL REPORT

May 24, 1965

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Union Carbide Corporation
Carbon Products Division

Fostoria, Ohio

R97-39455

UNION CARBIDE

UNION CARBIDE CORPORATION

CARBON PRODUCTS DIVISION

P. O. BOX 191, FOSTORIA, OHIO

May 24, 1965

Contracting Officer (20)
c/o Mr. M. C. Owens
NASA Manned Spacecraft Center
Procurement and Contract Division
Houston, Texas

Subject: Final Report Contract NAS 9-3699
"Carbon Electrode Development Program"

Dear Sir:

Attached are twenty copies of the final report summarizing results of the entire six months' program carried out under contract NAS 9-3699. This work began on November 3, 1964, and was completed May 3, 1965.

We feel that results of the present study have been useful in demonstrating the superiority of the carbon arc as a solar simulating source. Major accomplishments resulting from this study have been the development of a completely reliable carbon electrode joint, and of carbons which operate with less than 10% of the troublesome particle ejection (sputtering) exhibited by 16mm carbons available prior to this program. A lot of 700 16mm carbons incorporating these improvements will be supplied to the NASA as specified in the contract. Fifty of these pieces are being shipped this date. By special arrangement with your office, the remaining 650 pieces will be shipped to Houston during the last week of June.

Your attention is invited to our March 19 technical proposal for an extended study in this area. This study would make use of the valuable information generated during the present investigation in further perfecting 16mm carbons for use in the MSC simulator. Specifically, further core composition studies are proposed to improve the spectral match of the carbon arc to that of the sun while reducing sputtering still further. In addition, measurement of the spectral energy distribution is proposed in the 0.25 to 2.5 micron range on the improved carbons operated in the MSC simulator. This information is essential in the interpretation of results from many of the experiments which are to be performed in the MSC solar simulation facility.

Early approval by the NASA of funds needed to activate this program extension will insure continuity of effort required in reaching our mutual objectives. We will be looking forward to hearing of your decision on this matter.

Very truly yours,

E. L. Piper

Division Manager
Fostoria Development Laboratory

E. L. Piper:sp
attach.

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Union Carbide Corporation
Carbon Products Division
Development Laboratory
Fostoria, Ohio
May 24, 1965

1.0 Introduction

This report summarizes the results of development work performed under Government Contract No. NAS 9-3699 during the period November 1964 through May 1965. The objective of the contract was to develop improved 16mm solar positive carbon electrodes for use by the NASA Manned Space Center. Principal improvements in the electrodes sought in the contract studies were stronger, more reliable carbon joints and the elimination or minimization of arc sputtering. Other improvements which are desirable could not be made within the limitations of time and manpower for Contract No. NAS 9-3699.

Section 2.0 of this report summarizes the development work on electrode joints. This work was designed to increase joint strength and minimize arc sputtering during the burning of joints. Section 3.0 treats the study of core formulations, which was undertaken for the purpose of reducing arc sputtering in unjoined electrode sections. In Section 4.0, the manufacture of a limited production run of carbon electrodes having the most improved composition is described. The contractor will deliver to the NASA Manned Space Center 700 electrodes made from this best composition and embodying all improvements described in this report. A process flow diagram showing the manufacturing operations involved in making solar arc carbons is included in Section 4.0 for the benefit of readers who are not familiar with arc carbon manufacture. Section 5.0 states conclusions and recommendations which are based upon work performed under the contract.

2.0 Carbon Joints Adapted for the NASA-MSC Solar Simulator

2.1 Improved Joint Strength by Means of Better Core-to-Shell Bond

2.11 Background - Initial studies of joint design in a previous program showed that the cement used to bond cores to shells in 16mm solar positives was not adequate if the application required the carbons to be joined for continuous operation in solar simulators. Although the cement is adequate in commercial applications, non-uniform joint strengths resulted when threaded joints were machined on finished carbons. It was evident from the nature of the joint breakage and the wide spread in torque required to break joints, that the amount of cement present in the annular space between core and shell varied from carbon-to-carbon. Because of this fact, earlier joint designs were based upon the strength contributed from the shell only, and no contribution was made by the core. Investigation on coreless carbons of various thread forms and pitch diameters showed that a 37/64-18 NS truncated thread gave the highest lower 3-sigma strength in torsion. The optimum length of the joint for this thread was found to be 7/32". This length gave minimum arc disturbance and strength comparable to that for other lengths tested. Figure 1 is a sketch of three joints having different tolerances and Table 1 lists the torque required to break five joint forms tested.

TABLE 1

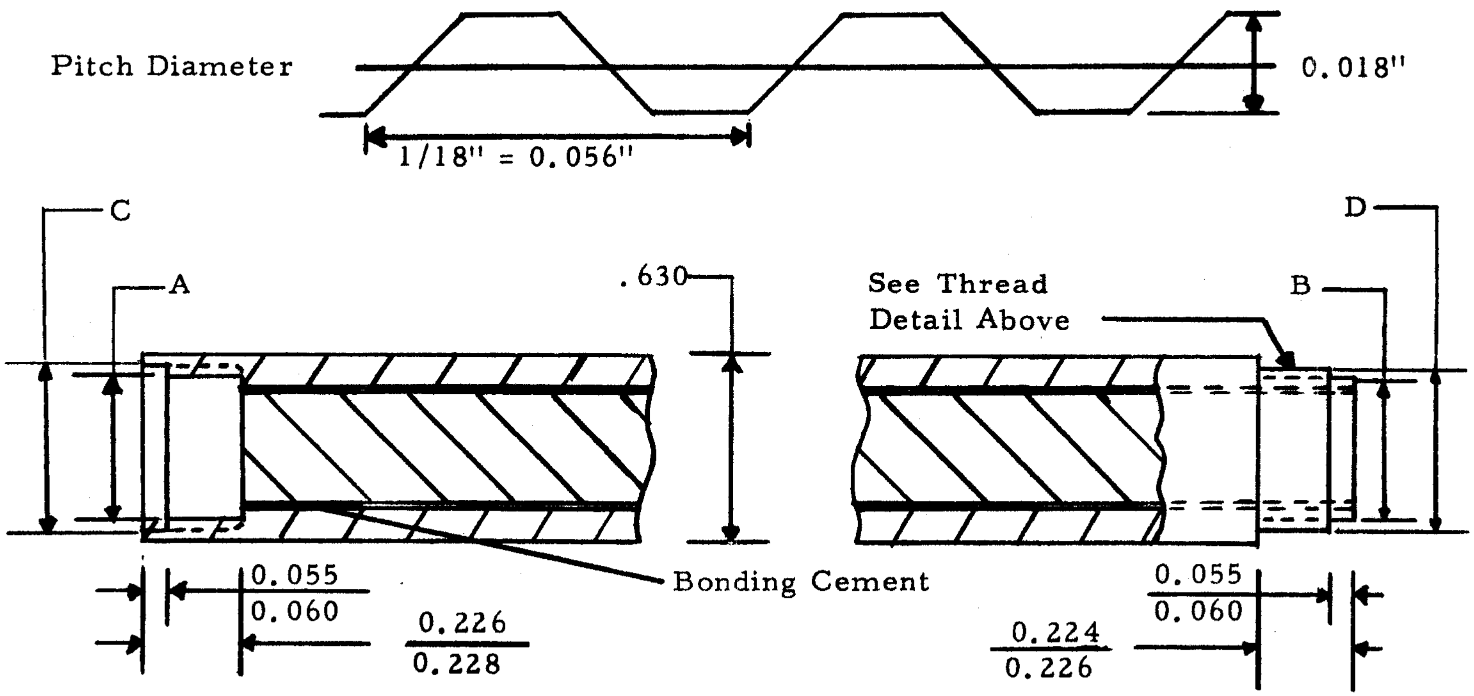
Torque Required to Break Joined Carbon Shells Having Various Thread Forms *

Thread Form -	9/16-27	Round Thread	9/16-18	37/64-18	19/32-18
No. of Samples	20	19	20	20	21
Avg. breaking torque, $\bar{X}$, in-oz	188	138	176	174	175
Standard deviation, σ	49.7	34.6	42.1	15.7	35.1
$\bar{X}-3\sigma$	39	34	50	126	70
Sample failed at socket, %	15	5	0	20	95
Sample failed at tang, %	85	95	100	80	5

*Data in table established before the inception of this contractual period and published in Intra-Company Memorandum - J. T. Cedargren, TMC-91, "Solar Arc Carbon Joint Design, Testing, and Production," July 9, 1964.

FIGURE 1

Truncated Thread Joint Design



9/16-18 NS

A	B	C	D
.516 / .514	.510 / .508	.544 / .542	.538 / .536

9/16-18 NS Revised

A	B	C	D
.514 / .512	.510 / .508	.544 / .542	.540 / .538

37/64-18 NS

A	B	C	D
.530 / .528	.522 / .520	.564 / .562	.556 / .554

2.12 Improved Joint Strength by use of a Resin Bond Between Shell and Core Cured at 110°C - Work under the present contract was initiated with a study to increase joint strength by using the core as a structural member of the joint. Since no strength measurements were available on the core material itself, the torque required to break standard cores was determined. The present standard cores (0.446" diameter) broke at an average torque of 740 in-oz, and a lower 3-sigma torque of 655 in-oz. Comparison of the torques at which the cores broke with those at which the 37/64-18 NS threaded shell broke (shown in Table 1) indicated that the core can contribute materially to the over-all strength of the joint. These torque values were determined by breaking forty core samples. The test equipment consists of a Rivett turret lathe with the turret replaced by torque transmitting and sensing devices mounted on the lathe ways. The torque transmitting members are a Zagar collet chuck and its connecting shaft cradled by two bearings which are coaxially mounted with the lathe spindle. The connecting shaft is joined directly to the shaft of a bracket-mounted torsion sensing device. A Sanborn strain gage recorder amplifies the signal from the electrical resistance strain gage of the torque sensor and records the result on a strip chart. The connecting shaft is designed to allow the Zagar collet chuck to travel axially during threading of a joint. A photograph of the apparatus is shown in Figure 2.

One approach to utilizing the core as a structural member of joints is to provide a strong, reliable bond between the core and the shell. The carbon shell on the tang of the joint, supported by the core, may be decreased in thickness permitting a proportionate increase in socket wall thickness. A joint with increased strength can be expected from this change in design. Twenty-three inch long carbon shells, 16mm in diameter, and cores with appropriate diameters were assembled by painting the core with epoxy resin, slipping the core into the shell, and curing in air at 110°C for 8 hours. The epoxy resin system used was 100 parts ERL-2795 resin[1] and 20 parts ZZL-0816 hardener.[1] The twenty-three inch long rods were cut into 4" long segments, on which tangs and sockets were machined. A 9/16-18 NS truncated thread was selected because it provides the maximum socket wall thickness consistent with the minimum practical tang shell thickness obtainable with standard taps and dies. Samples machined with the two variations of this thread form shown in Figure 1 were prepared. These forms are identical except for the thread clearance between tang and socket. The torques required to break joints having these two variations of the 9/16-18 NS truncated thread form were measured. The results are listed in Table 2. As is indicated, three types of breaks occurred: (1) the tang

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[1] Catalog nomenclature of Union Carbide Plastics Division

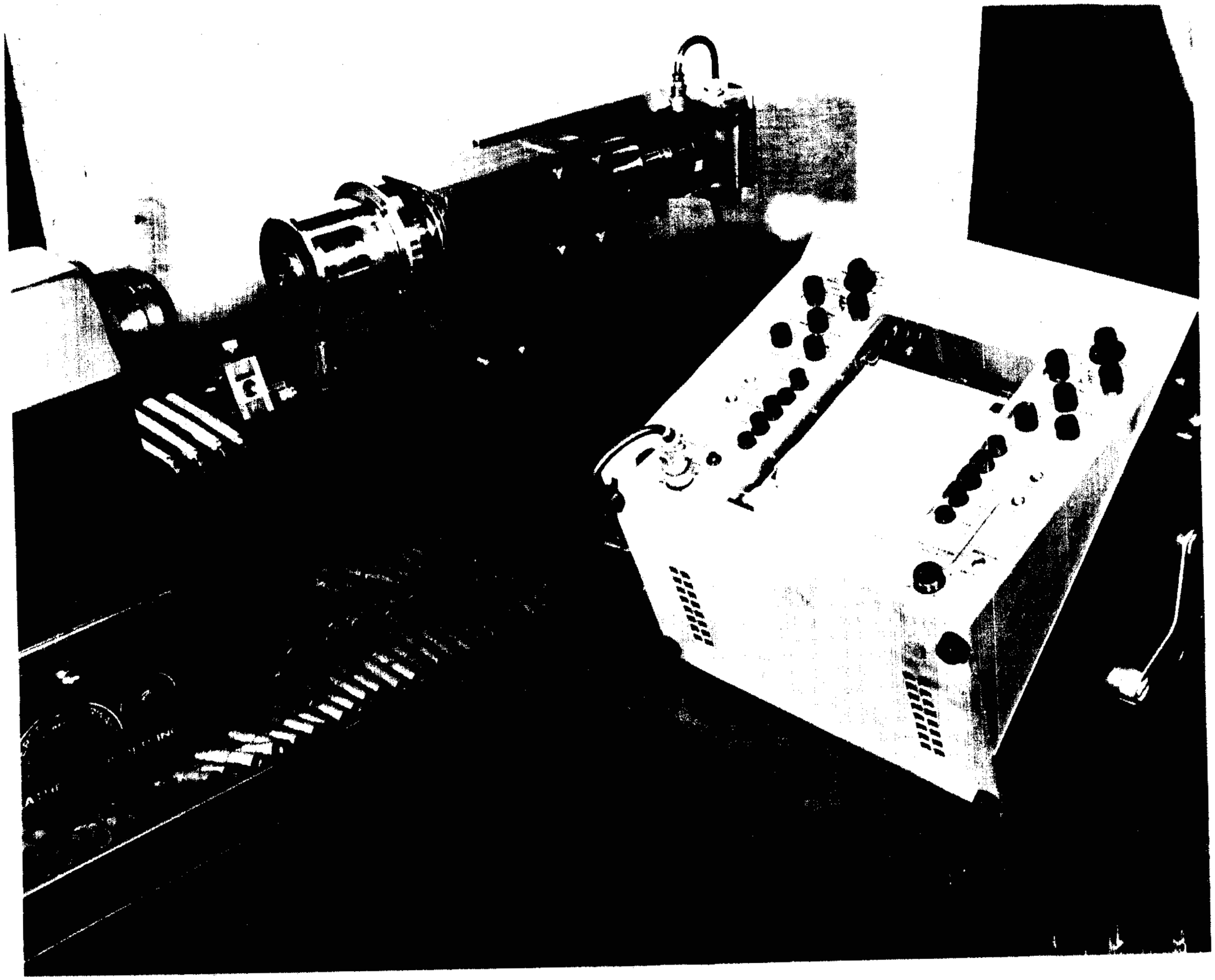

FIGURE 2. Arrangement of Torsion Testing Equipment

TABLE 2

Torques Required to Break Joints on 16mm Solar Positives

Torque to Break Joint, In-Oz.

9/16-18 NS (Clearance = 0.004 - 0.008")		9/16-18 NS Revised (Clearance = 0.002 - 0.006")	
245 T	210 TS	280 PT	280 TS
190 TS	330 PT	240 T	290 PT
260 TS	290 PT	290 TS	310 PT
330 PT	265 TS	340 PT	315 PT
320 PT	170 TS	335 PT	250 TS
270 TS	290 TS	325 PT	350 PT
250 PT	110 (1)	360 PT	340 PT
280 PT	290 TS	320 PT	270 TS
320 PT	360 PT	335 PT	190 TS
255 T	335 PT	265 T	335 PT
325 PT	315 PT	375 PT	275 PT
300 TS	340 PT	260 TS	300 PT
395 PT	320 PT	250 PT	270 PT
310 PT	325 PT	270 TS	295 PT
275 T	210 TS	290 PT	245 TS

Σx_{29}	= 8375	Σx_{30}	= 8850
$\overline{X}_{29}$	= 288.8	$\overline{X}_{30}$	= 295
$\Sigma(x_i - \overline{X})^2$	= 75,389	$\Sigma(x_i - \overline{X})^2$	= 50,200
σ^2	= 2692	σ^2	= 1731
σ	= 51.8	σ	= 41.6
3σ	= 155.4	3σ	= 124.8
$\overline{X} - 3\sigma$	= 133.4	$\overline{X} - 3\sigma$	= 170.2

Samples with perfect tangs (PT)
from both groups

$\overline{X}_{36}$	= 317.6
$\Sigma(x_i - \overline{X})^2$	= 36,470
σ^2	= 1040
σ	= 32.2
3σ	= 96.6
$\overline{X} - 3\sigma$	= 221.0

(1) Split in socket - neglect, T - Tang only broke, TS - Tang slightly cracked and socket broke, PT - No crack in tang after socket broke.

only broke, (2) tang shell slightly cracked and socket broken, and (3) socket only broken with no cracks in the tang. It was observed that the first two types of break occured only when the tang shell was not bonded to the core over the entire circumferential mating surface. Breaks of the first and second type accounted for the lower torque measurements. If only joints exhibiting the third type of break are considered, the mean and lower 3-sigma strength values are much higher than strengths realized with the best previous joint (37/64-18 NS in Table 1), where only shell wall strength was considered. These data indicate that a strong bond present in the annular space between the shell and core will result in a mean joint strength of approximately 300 in-oz and a lower 3-sigma value of over 200 in-oz, when 9/16-18 NS truncated threaded joints are used.

Since some tangs broke, even with the strong epoxy resin cement used above, while others remained intact during testing, a method of applying the cement with more reliability appeared necessary. A grease gun was fitted with the coupling shown in Figure 3 so that the resin could be forced under pressure into the annular space between the core and the shell. As a first attempt, 5" long, 16mm shells fitted with cores were assembled by holding the gun and coupling in a vise and the carbon in hand, and forcing the resin into the ends of the rods. In order to use this method, a different resin system with a longer pot life was used in place of the former epoxy system. The formula of the resin is as follows (weight percent):

50% ERL-3794 epoxy resin[1]
25% BRP-5012 bakelite phenolic resin[1]
12.5% furfuryl alcohol[2]
12.5% furfuryl aldehyde[2]

One lot of samples was prepared by painting resin on the cores and slipping the cores into the shells. Another lot was made by forcing the resin into the annular spaces by use of the grease gun. Each lot was cured in air for 8 hours at 110°C. Table 3 lists the torque required to break 9/16-18 NS joints on each lot of samples. As can be seen, the injection method of applying the resin is superior to the painting method, especially since no tang failures were experienced on carbons prepared by the former method.

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[1] Catalog nomenclature of Union Carbide Plastics Division

[2] Quaker Oats Company

FIGURE 3

Grease Gun Coupling

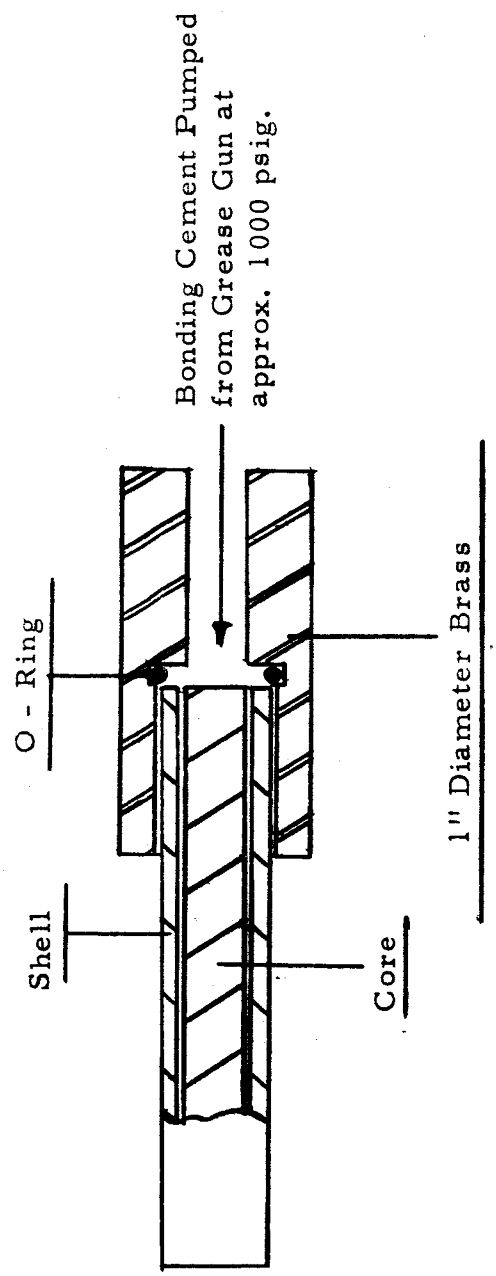


TABLE 3

Torque Required to Break Joints Having
9/16 - 18 NS Threads on 16mm Solar Carbons

Test No.	Resin Painted onto Cores Before Slipping into Shells: Torque In-Oz	Resin Forced into Annular Spaces with Grease Gun: Torque In-Oz
1	255 PT	290 PT
2	235 TO	265 PT
3	245 TS	275 PT
4	230 PT	295 PT
5	290 PT	320 PT
6	270 TS	275 PT
7	270 PT	280 PT
8	250 TS	305 PT
9	250 PT	280 PT
10	250 PT	275 PT
11		265 PT
Σx_i	= 2545	= 3125
$\overline{X}$	= 254.5	= 284.0
$\Sigma(x_i - \overline{X})^2$	= 2872.5	= 3051
σ^2	= 319.17	= 305.1
σ	= 18.0	= 17.5
3σ	= 54.0	= 52.5
$\overline{X} - 3\sigma$	= 200.5	= 231.5
% Tang Failures	50	0
% Perfect Tangs	50	100

TO - Tang only broke, TS - Slight crack in tang after socket broke,
PT - No cracks in tang after socket broke.

A holder was constructed to grip the carbon rods during resin injection, and 120 carbons rods, 16mm by 31 inches long, were prepared for experimental use. The mean torque required to break 9/16-18 joints machined on this lot of assembled carbons was 305 in-oz, and the lower 3-sigma limit was 205 in-oz. Again no tang failures occurred. Burning through the joints of these carbons at 400 amperes and 80-81 volts showed that the magnitude of the light fluctuation is less and the duration of maximum disturbance is comparable to those observed on standard 16mm solar positives now manufactured by Union Carbide Corporation (see center light traces in Figure 4).

Approximately 100 additional carbons were assembled using the phenolic-epoxy resin and the resin injection method. These carbons were sent to the RCA Service Company where a conical threaded joint was machined on the carbons. Fifty of the machined carbons were returned to Union Carbide for testing purposes, while RCA used the other carbons for tests in the NASA-MSC burner. RCA engineers found that although the strengths of the joints were adequate, deposits which accumulated on the positive contacts during burning were so severe that the carbon rods seized in the contacts and arc outage resulted. These deposits were also observed at the Fostoria Laboratory when the carbons with the epoxy-phenolic bond were burned in a conventional arc lamp. This phenomenon was not entirely unexpected in light of previous company experience with resin bonds. The main goal of the experiment, however, was to show that the strength of threaded joints could be increased when a strong bond between shell and core existed.

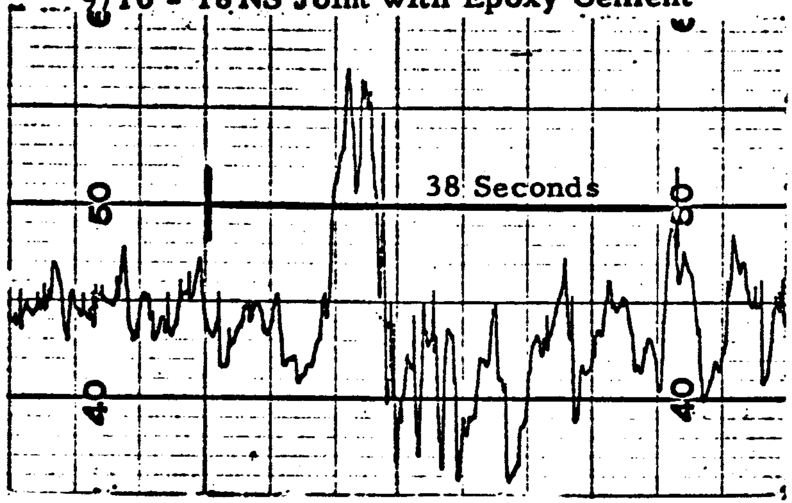
Probably the excessive deposits on the positive contacts were caused by volatile constituents of the epoxy-phenolic resin bond, which had been cured in air at a temperature of 105-110°C. This relatively low curing temperature was used to avoid reduction in bond strength. After it was demonstrated that these carbons fouled the positive contacts, burning trials were made with carbons cured at higher temperatures. Curing temperatures of 200°C and 300°C reduced the amount of deposits on the contacts, but the deposits were still excessive. At a curing temperature of 400°C, fouling was eliminated but the bond strength was substantially lost.

Another approach to reducing or eliminating deposits on the contacts is to reduce the amount of resin used to bond the core in the shell. To test this approach, approximately 50 carbons were prepared using this resin with the amount and duration of pressure applied during resin injection controlled to limit the length of resin penetration into the annular space to about 2 inches at each end of the carbon. Five to seven inches of penetration had resulted in the first lot of carbons prepared. Following a resin curing at 110°C in air for 8 hours, these carbons were machined with 9/16-18 NS

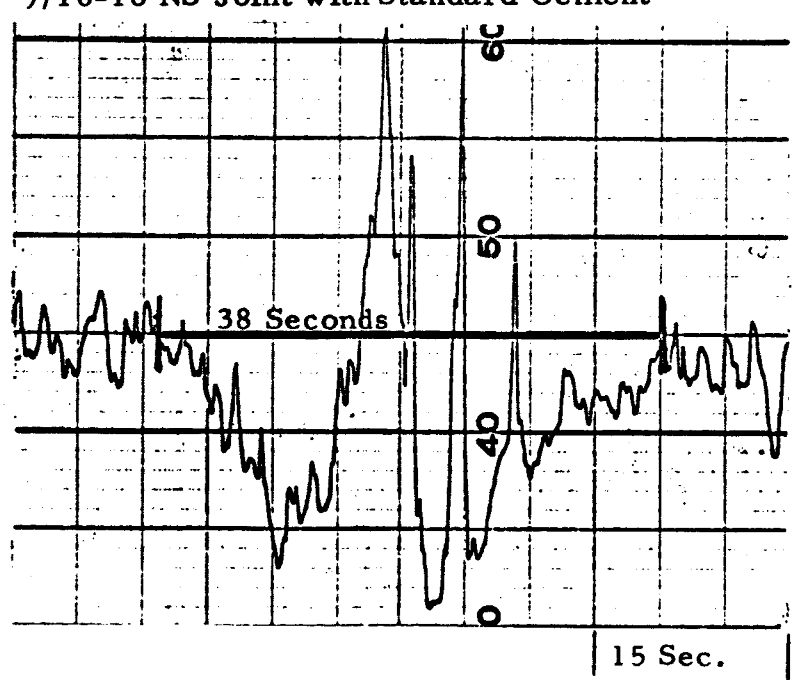
FIGURE 4

Relative Center Light for Joint Burnthrough
Epoxy Resin Cement Vs Standard Cement

9/16 - 18 NS Joint with Epoxy Cement



9/16-18 NS Joint with Standard Cement



Note: Ordinate represents percent scale deflection of a Honeywell Millivolt recorded bridged across an ammeter. Chart speed was 4" per minute. The ammeter was connected to a Weston Photocell placed at the center of the light pattern at a distance of 15 feet from the arc. A lens and 0.301" stop was placed in the light train at 7.45" from the arc and a 5/8" stop placed at the photocell.

truncated thread joints. Nineteen of these carbons were burned in the MSC carbon arc burner in a test involving 9-1/4 hours of continuous operating time. No seizing problems occurred during this test, but examination of the positive contacts after conclusion of the test disclosed deposits of a soft black residue. This condition would not be satisfactory for a test lasting for an extended period of time. All of the 9/16-18 NS truncated thread joints burned in this test (19 joints) had adequate strength, and no joint failures occurred during the test. Breaking torque given in Table 4 show good agreement between test results obtained on threaded joints on the Fostoria Laboratory and RCA test rigs. In addition, good uniformity of strength for these joints is indicated by the relatively low standard deviations. The strengths of the truncated threaded joints appear higher than for the conical joint as seen from data in Table 4.

TABLE 4

Test Rig	Number of Joints Tested	Joint Design	Mean Torque Required to Break Joints, in-oz	Standard Deviation	Lower 3-sigma Limit	Range in-oz
Fostoria Laboratory	10	9/16-18 NS	313	29	225	270-370
RCA	10	9/16-18 NS	313	19	256	290-350
Fostoria Laboratory	9	RCA Conical	190	41	67	135-280
Fostoria Laboratory	10	RCA Conical	174	34	72	90-220

2.13 Improved Joint Strength by Use of a Bond Between the Core and Shell which is Cured at High Temperatures - To obtain carbon joints with maximum strength, a strong bond between the entire circumference of the core and the I.D. of the shell on the ends of solar carbons is required. As shown earlier, a 110°C-cured epoxy-phenolic resin mixture will provide adequate strength, but this resin causes fouling of the positive electrical contacts in the carbon burner. Thus a carbonaceous cement is needed which will meet the strength requirements after it has been baked to a temperature high enough to eliminate fouling of the burner contacts due to volatile condensation.

Experimental cement compositions were prepared from resins and pitch-resin mixtures with graphite and gas blacks added as fillers. Several of these cements were too viscous at room temperature to be injected into the annular space between the core and shell. The carbons were therefore bonded with these cements by fitting the core into the shell with one end (of the core) protruding 2 to 3 inches, painting cement onto the protruding end of the core, forcing the coated end of the core into the shell, and repeating the process to bond the carbon on the opposite end. Approximately forty carbons were assembled with each of eight different cement compositions. Of the forty carbons bonded with each cement, ten pieces were cured at 110°C to 125°C, ten pieces at 330°C to 350°C, ten pieces at 390°C to 410°C, and ten pieces at 480°C to 520°C. Four different curing temperature ranges were used so that the effect of this variable on contact fouling and on joint strength could be studied. The preferred curing temperature is the highest temperature at which the bond still retains adequate strength.

After the bond cement had been cured, the carbons were machined with 9/16-18 NS truncated thread joints. Strength of the bond obtained with the different cement compositions was determined by measuring the torque required to break the joints. On 9/16-18 NS truncated thread joints having adequate bond strength between shell and core, the male tang shell, supported by the core, exceeds the strength of the socket. Therefore when the torque required to break such joints is generated, the point of failure is always the socket. The nature of the break is then an indication of the strength of the bond; if the socket breaks, the strength of the cement is adequate; if, on the other hand, the tang shell breaks away from the core, the strength of the cement is not adequate.

One cement composition was superior to the others based upon the torque required to break the joints and upon the appearance of the male tangs after the joints were broken. Fifteen joints machined on the carbons bonded with each cement were tested to determine the torque required to break them. Five carbons with the cements cured at 100°C to 125°C, five at 330°C to 350°C, and five at 480°C to 520°C were tested. None of the tangs on the carbons bonded with the superior cement broke, nor was there any evidence of bond failure. Many of the carbons bonded with the other cement compositions, including most of those which had been cured at 480°C to 520°C, showed evidence of bond failure in the form of broken or chipped tangs.

The cement composition which appears superior to the others tested consists of a resin-pitch mixture with a powdered graphite filler. The formula of the cement is as follows:

100 parts ERL-2795 epoxy resin[1]
25 parts Coal Tar Pitch with a softening point of 90-95°C
25 parts High Purity Artificial Graphite
25 parts Trimellitic Anhydride

Because a suitable apparatus was not available to inject this cement into the space between the shell and core, it was decided to use the painting method to assemble carbons with the new cement. The major portion of 3000 carbons prepared in this manner was supplied to RCA, while the remainder was used by UCC for testing purposes.

As one step in determining the optimum curing temperature, carbons from the above lot were cured at the following temperatures: 115°C, 300°C, 315°C, 325°C, and 440°C. After the carbons were cured, conical joints were machined on the ends and the joints were broken on the torque measuring equipment which has been described earlier in this report. The breaking strengths from these tests are given in Table 5.

TABLE 5

Strength of Conical Joints vs. Curing Temperature of Bond Cement

Curing Temp. of Bond Cement	No. of Joints Tested	Mean Torque, in-oz	Torque Range, in-oz	Lower 3-sigma Limit, in-oz
115°C	12	214	170-260	111
300°C	12	224	155-260	105
315°C	12	179	120-230	75
325°C	12	164	120-200	86
440°C	12	175	100-245	42

The data in Table 5 show that the bond cement retains good strength after curing at temperatures as high as 440°C.

Further experiments performed to determine the optimum curing temperature for the bond cement were (1) measurement of the thermal expansion of the cement during curing and (2) a differential thermal analysis

[1] Catalog nomenclature of Union Carbide Plastics Division.

(DTA). Thermal expansion measurements made while the cement was being cured showed that it expands with increasing temperature up to 370°C. Increasing the temperature beyond 370°C causes the cement to contract. During the thermal expansion measurements, in the temperature range 300°C to 350°C, the evolution of a large amount of condensible gas was observed. The DTA analysis showed a significant exothermic peak between 350°C and 370°C, and a broad exotherm above 370°C. The exothermic peak is consistent with the gas evolution, while the broad exotherm above 370°C corresponds to the onset of shrinkage of the cement. Consideration of the foregoing information, especially the pronounced shrinkage which occurs above 370°C, led to the selection of 350°C as a maximum curing temperature for the bond cement.

About 50 carbons bonded with the resin-pitch cement were cured at 350°C in preparation for burn testing. The purpose of this burn test was to determine whether the bond cement after baking at 350°C would cause fouling of the burner contacts. Before the test was started, the burner contacts were cleaned thoroughly. The burner was then operated for 12 hours with the sample carbons, after which the contacts were examined for deposits. No difficulties occurred during the test and the I. D. of the burner contacts had only a very thin coating which was graphitic in appearance.

Uniform and complete filling of the annular space between core and shell at the ends of solar carbons is an important factor in assuring uniform joint strength. The importance of uniform resin distribution is evident from data obtained in evaluating the effect of curing temperature upon bond strength. The carbons for which joint strength was reported in Table 5, page 14, were examined for chipped threads on the male tangs prior to testing. Chipping of threads occurs during joint machining and is an indication of incomplete filling of the annular space with bond cement. In Table 6, the average strength and the range of strength are compared for the total number of pieces tested vs. the pieces with unchipped tangs. These results show that both the average strength and the range of strength are consistently higher for the joints having unchipped tangs.

TABLE 6

Effect of Chipped Tangs on Strength of Conical Joints

Curing Temp. of Bond Cement	Total No. Pieces Tested/ No. Pieces with Unchipped Tangs	Mean Torque, in-oz Total Pieces/ Unchipped Pieces	Torque Range, in-oz Total Pieces/ Unchipped Pieces
115°C	12/5	214/231	170-260/210-260
300°C	12/5	224/254	155-260/230-295
315°C	12/4	179/193	120-230/150-230
325°C	12/4	164/170	120-200/150-190
440°C	12/2	175/212	100-245/210-215

This data indicates strongly that a reliable method of placing cement uniformly around the 360° of annular space between shell and core is necessary to obtain a high strength threaded joint, and especially a conical joint where the thread is traced through the shell-core interface.

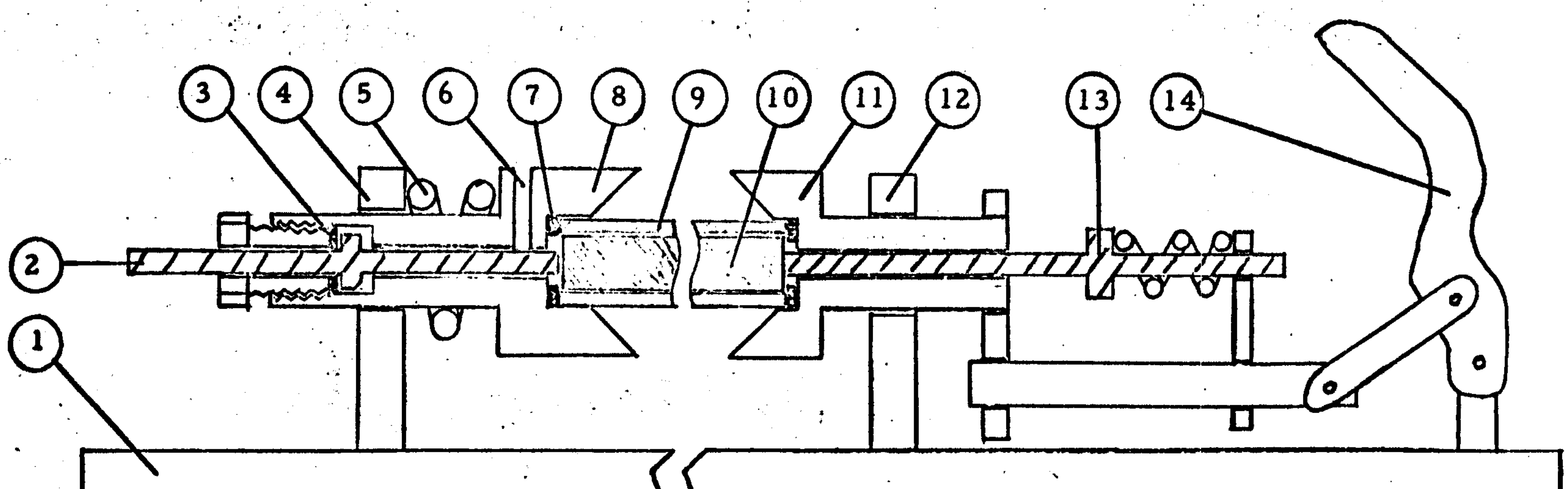
A cement injection apparatus was designed and built at no cost to the contract fund, and a sketch of the apparatus is shown in Figure 5. The function of this device is to inject the cement into the entire 360° of annular space between the core and shell for a distance of at least 3 inches. The general procedure used for bonding carbons with this device is as follows: (1) place the core inside the shell, (2) clamp the shell, with core inside, in the bonding device, (3) turn on the positive displacement pump and adjust it to accumulate desired pressure on cement, (4) open valve allowing the cement to flow into the annular space for a specified number of seconds, (5) close valve, (6) remove carbon from device, and (7) wipe ends clean.

Obtaining distribution of the cement over the full 360° of annular space proved to be a difficult problem. The following methods were tried and found unsuccessful: (a) pumping cement at room temperature directly into the annular space, (b) pumping cement into the annular space with copper conveyor tubes and head of bonding device heated to 50°C, (c) vibrating the core by means of a vibrator and steel extension shaft while pumping the cement into the annular space, (d) cutting axial grooves in the surface of the core to provide channels for the cement, (e) heating the cement to 55°C before injecting it into carbons with axially grooved cores, (f) rotating the core after injection of the cement to smear it over the entire circumferential mating surface of shell and core interface.

FIGURE 5

SKETCH OF CEMENT INJECTION APPARATUS

1	Channel iron stand	6	Cement channel (cement delivered from positive displacement pump)	10	Carbon core
2	Rotatable shaft	7	Gasket	11	Retractable head
3	Gasket	8	Head	12	Slide-way for head
4	Slide-way for head	9	Carbon shell	13	Spring-loaded, rotatable shaft
5	Spring			14	Retracting mechanism



The method which did prove successful was the use of shells having protruding ribs on their inside diameters. These ribs center the core within the shell and permit the cement to flow into the entire 360° of annular space. To test the effectiveness of ribbed shells without the time delay usually required for carbon processing, shells containing four equally-spaced ribs were extruded from a resin bonded carbon mix. After the resin bonded shells had been cured at a low temperature, these shells had sufficient strength for use in performing the required tests on the flow of the bond cement in the annular space. The four ribs protruded about 0.006", were 0.030" wide, and were located 90° apart on the inside diameters of the shells. Using the ribbed shells in the bonding device, 360° filling of the core-to-shell annular space with cement for a distance of 3 inches was obtained.

The original model of the bonding device injected resin into only one end of the carbon, making it necessary to remove the carbon, turn it end for end, and repeat the procedure to bond the other end. A second cement injecting head has been installed on the cement injection device and used successfully to inject cement simultaneously into both ends of carbons having ribbed shells.

Concurrently with the design and construction of the injection apparatus, experiments were conducted in an attempt to find a cement with a longer pot life and/or higher strength than the original epoxy-pitch-filler system. Although the pot life of the resin-pitch-graphite cement which has been described above is long enough to permit its use for the production of solar carbons, a longer pot life is desirable to simplify production operations. The pot life of this cement at 25°C is shown by the viscosity versus aging-time curve in Figure 6. The increased pot life - up to two days - which can be obtained by storing the cement at 10°C is also shown in Figure 6.

A series of 30 different cement compositions was prepared from resin mixtures having a pot life expected to be longer than that of the resin whose composition is given on page 14. Initial evaluation of the modified cements was based upon (1) their appearance as polymerization took place at 115°C and (2) both the amount of residual material and its structure after various stages of pyrolysis. Based upon these criteria, two cement compositions appeared superior to the others. These are shown in Table 7.

FIGURE 6

Pot Life of Resin-Pitch-Graphite Cement

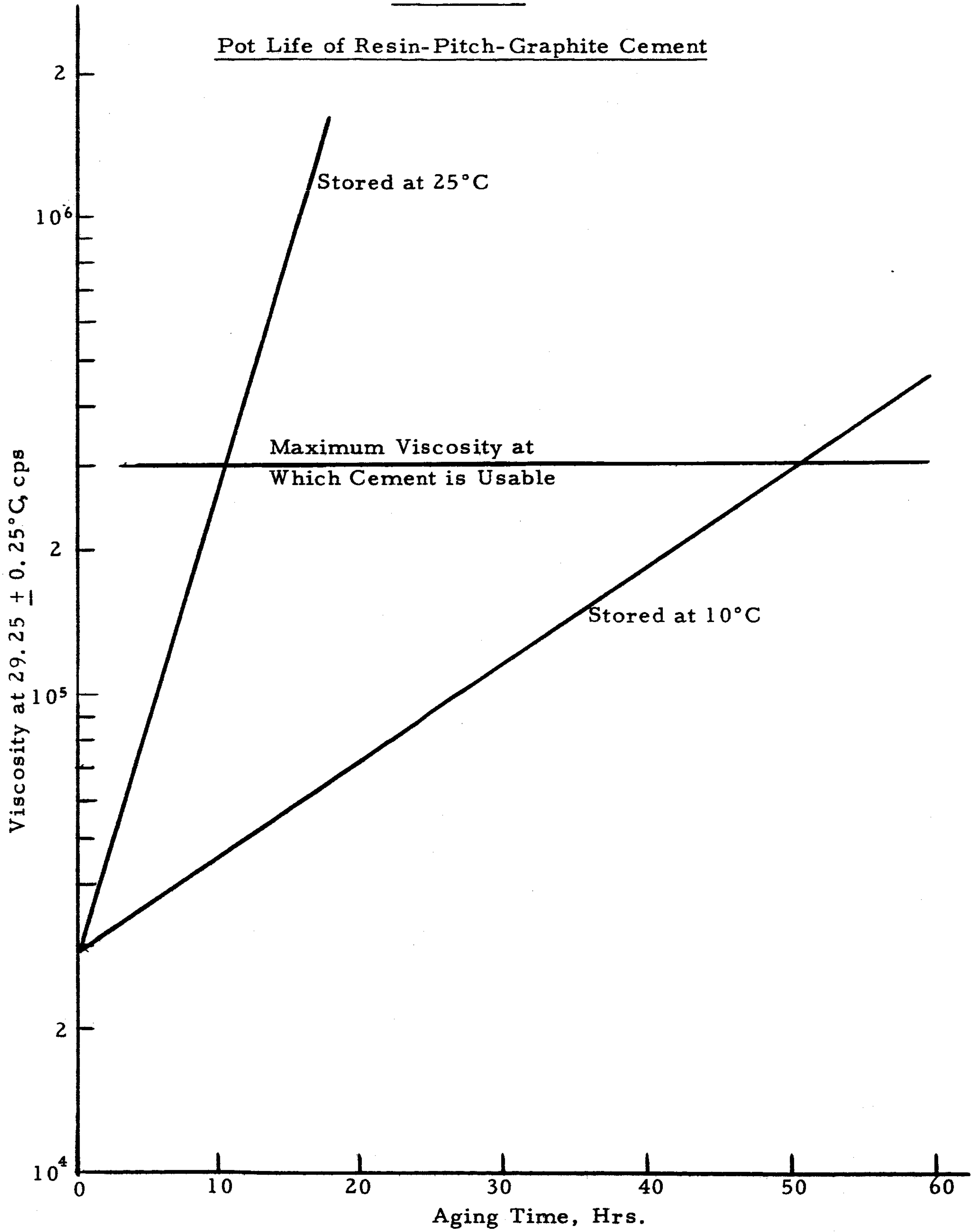


TABLE 7

Cement Composition				Residual Material after Curing, %			
I. ERL-2795 parts, wt.	Graphite parts, wt.	TMA parts, wt.	Coal Tar parts, wt.	350°C	400°C	500°C	Appearance of Cured Resin
1. 100	25	25	25	58.2	53.1	48.6	Hard residue with increased porosity as pitch content and curing temperature increased.
2. 100	25	25	15	58.7	50.2	48.5	
3. 100	25	25	10	57.4	51.3	49.8	
II. ERL-3794 parts, wt.	Graphite parts, wt.	TMA parts, wt.	Coal Tar parts, wt.				
1. 100	25	25	25	72.2	68.8	62.1	Hard, dense residue with less porosity than cement above, but increased porosity with increased pitch content and curing temperature.
2. 100	25	25	15	73.3	68.3	62.3	
3. 100	25	25	10	74.4	67.5	65.7	

About fifty 16mm by 30 inch solar carbons were bonded with each of the two cements shown in Table 7 using the cement injection apparatus described earlier. The composition of the two cements, hereafter referred to as cement A and B, are shown in Table 8.

TABLE 8

Composition of Core-to-Shell Bond Cements

Ingredients	Cement A * Parts by Wt.	Cement B * Parts by Wt.
TMA Catalyzed epoxy resin, ERL-2795	125	-
TMA Catalyzed epoxy resin, ERL-3794	-	125
Graphite Flour	25	25
Coal Tar Pitch	25	-

* Composition of cement A is shown in Table 7 as I. Cement B was formulated by deleting the pitch from the epoxy-graphite system shown as II in Table 7. This was necessary to reduce the viscosity of the cement so that it can be injected into annular space between core and shell. Using the residual material data of II in Table 7 at a curing temperature of 350°C, the system with zero parts pitch was shown by calculation to give 75.6% residual material.

Shells used for these carbons had six protruding ribs on their inside diameter to center the core and to permit uniform filling of the annular space with cement. The assembled carbons were cured at a temperature of 350°C, then machined with conical threaded joints by the RCA Service Company.

After the carbons had been machined, the threaded tangs were inspected visually. The degree of chipping of shell threads at the interface between the shell and core is indicative of the bond strength, adherence, and of the presence or absence of cement in the annulus. Table 9 shows the results of this inspection.

TABLE 9

Visual Inspection of Conical Threaded Tangs

Cement	Number of Carbons Inspected	Number of Carbons Having Chipped Threads	Percent of Carbons Chipped
A	25	25	100
B	23	9	39

The general appearance of the threads on carbons bonded with cement B was much better than that for cement A.

Measurement of the torque required to break the above mentioned conical joints provided additional information for a comparison of cements A and B. Carbons bonded with epoxy-phenolic cement and machined with conical joints were included in this test to provide a basis for judging the adequacy of joint strength. Although the carbons bonded with epoxy-phenolic cement do foul carbon burner contacts, they are representative of a lot of carbons which burned in the NASA-MSC simulator without joint breakage. Table 10 shows the results of joint strength measurements on carbons bonded with cements A and B, and with cured epoxy-phenolic cement.

TABLE 10

Torque Required to Break Conical Joints

	Bond Cement		
	Epoxy-Phenolic	Cement A	Cement B
No. of joints tested	9	10	10
No. of joint failures from:			
broken sockets	2	0	3
stripped threads	7	10	7
Mean strength, in-oz	190	167	228
Range, in-oz	135-280	145-210	200-265
Standard deviation, σ	41	22	25
Lower 3σ limit	67	100	153

The data in Tables 9 and 10 indicate that cement B is superior to cement A because:

(1) Visual inspection of joints on carbons bonded with cement B showed less shell thread chipping, indicating a stronger bond (Table 9).

(2) Both the mean strength and the lower 3-sigma limit are higher for joints machined on carbons bonded with cement B (Table 10).

2.2 Improved Joint Strength by Use of a Threaded Core Nipple

A core nipple joint, according to a design of RCA shown in Figure 7, was machined upon Union Carbide shells and cores. Excellent strength values were obtained with this design as shown in Table 11. The burning characteristics of this joint, however, are very poor and will be discussed in Section 2.3.

TABLE 11

Torque Required to Break Core Nipples

Test No.	Torque to Break Joint, in-oz	Remarks
1	300	Thread stripped, socket did not break
2	280	Socket broke
3	295	Nipple sheared in two
4	295	Nipple threads stripped, socket broke
5	315	Nipple sheared in two
6	290	Threads on nipple stripped
7	290	Socket broke
8	310	Nipple sheared in two
9	285	Nipple sheared in two

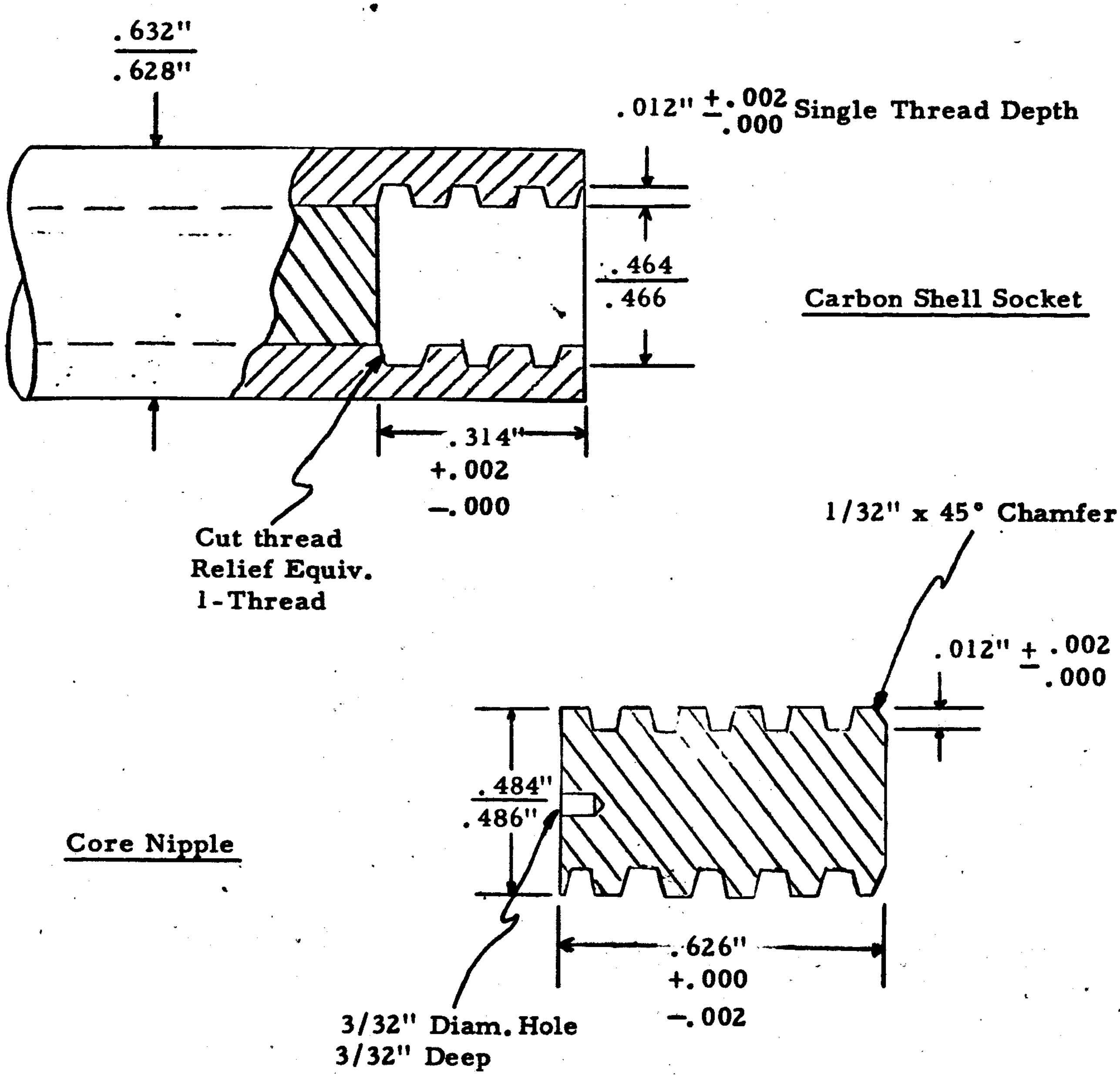
$$\Sigma x_i = 2660$$
$$\bar{X} = 295.6$$
$$\Sigma(x_i - \bar{X})^2 = 1022$$
$$\sigma^2 = 127.8$$
$$\sigma = 11.3$$
$$3\sigma = 33.9$$
$$\bar{X} - 3\sigma = 261.7$$

2.3 Effect of Joint Shape on Amount of Sputtering and on Light Fluctuation

An experiment was performed to demonstrate that most of the arc disturbance (light fluctuation) and particle ejection which occurs during joint burn-through is caused by the break in the core rather than that in the shell. Carbons were assembled both with a continuous core passing through a threaded shell joint, and with a core break in a continuous shell. This assembly permitted separate observation of the effects on the burning performance of breaks in the core and in the shell. Tests of these carbons showed that little light disturbance or effect on particle ejection result when the threaded shell joint burns through. When the carbon with the continuous shell and split core was burned, the arc disturbance and severity of particle

FIGURE 7

RCA Core Nipple Joint



ejection was very much greater than that observed in burning the carbon having a joined shell with an uninterrupted core. The recordings of light intensity fluctuations obtained during this experiment are shown in Figure 8. The results indicate that efforts to reduce arc sputtering during joint consumption should be concentrated on a study of the core break rather than the thread design or fit.

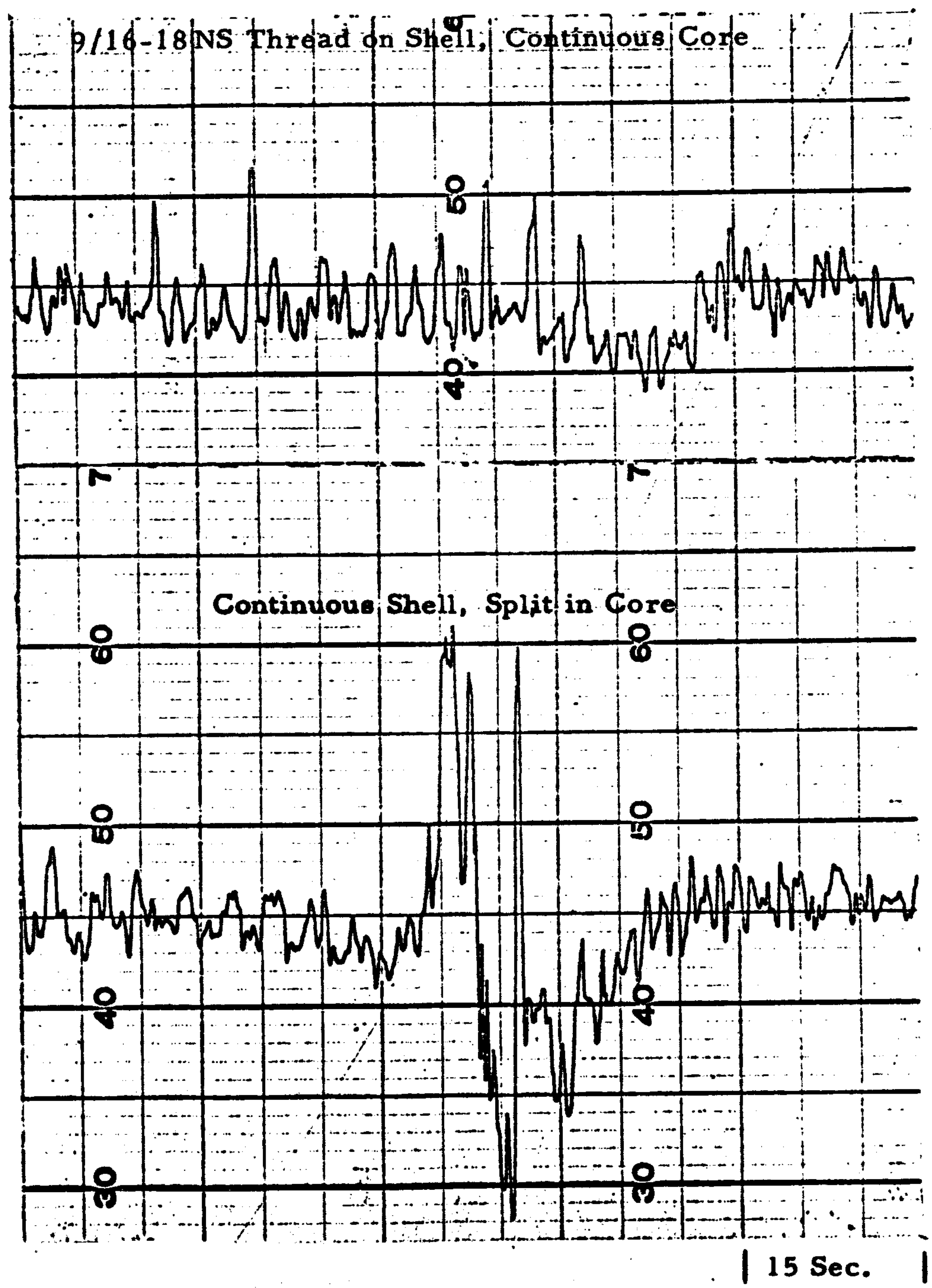
Results of this experiment explained the burning characteristics of the first three joint designs tested. These were the RCA conical joint, the 9/16-18 NS truncated joint proposed by UCC, and the high strength nipple joint developed by RCA. In tests conducted in the NASA-MSC simulator, a quantitative measure of sputtering showed that the conical joint sputtered the least, the nipple joint the most, with the 9/16-18 NS threaded joint intermediate. The use of quartz plates, weighed accurately before and after exposure to arc sputtering, provided a measure of the amount of sputtering. Not all of the particles ejected by sputtering hit the quartz plate and probably some which hit it do not stick. Hence these particles are not caught and weighed, however, each carbon joint is tested under the same conditions, so that the test is comparative and adequate for the purposes of this program. This method of measuring arc sputtering will be referred to as the Quartz Plate test.

Quartz plates used for this test are translucent, rough cut and unpolished. They are 5 inches in diameter by 3/16 inch thick and weigh 150 to 170 grams each. The plates are prepared for use in the following manner: (1) they are heated to 950°C in a furnace to eliminate moisture and bring them to constant weight; (2) after cooling they are weighed to an accuracy of ± 0.0002 gram, then placed in polyethylene bags; (3) the bags with plates inside are weighed to an accuracy of ± 0.0002 gram and tagged with an identification number; (4) the polyethylene bags containing the plates are overwrapped with moisture-proof foil bags and sealed until ready for use.

A stainless steel holder is used to support the plate in front of the arc during the test. The plate is placed at a distance of 4 inches from the front face of the positive contacts, perpendicular to the axis of the carbon with the center of the plate in line with the carbon axis. Joints are tested in the MSC burner by placing a quartz plate in the holder in front of the arc when the joint disappears from view at the back face of the positive contacts. The plate is left in place for exactly 3 minutes, during which time the joint is consumed, then it is removed. After it cools, the plate is returned to the polyethylene bag to preserve its condition for weighing and visual inspection.

FIGURE 8

Relative Center Light for Threaded Shell versus that for Split Cores



Much of the material deposited on the quartz plates by arc sputtering is loose and can become dislodged from handling. The polyethylene bags are essential to catch this loose material and obtain a satisfactory measure of arc sputtering.

Table 12 shows the degree of sputtering for the three joints mentioned above.

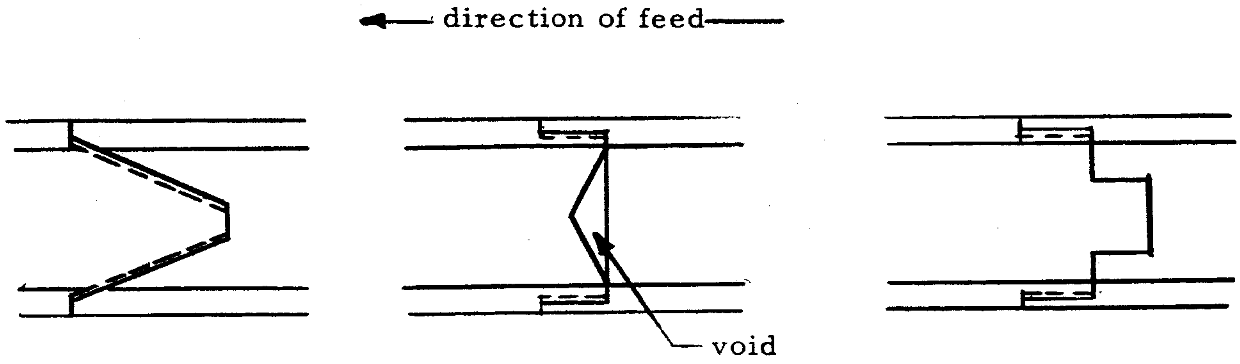
TABLE 12

Joint Design	No. of Joints Tested	Average Rate of Deposition of Material on Quartz Plate During Joint Consumption - mg. per minute
Nipple	4	5.3
9/16-18NS truncated thread	6	2.6
Coinical thread	2	1.2

Two other joints were designed in an attempt to reduce arc disturbance and sputtering by changing the geometry of the core break in the 9/16-18 NS threaded joint. These joint designs, along with the conical joint design, are sketched in Figure 9.

FIGURE 9

Proposed Joint Designs



Joint #1
RCA Conical
Threaded Joint.

Joint #2
9/16"-18 NS Truncated
Thread with Conical
Depression in Core of Tang.

Joint #3
9/16"-18 NS truncated
Thread With Core
Spindle on Tang.

Samples of each of the three joint designs illustrated in Figure 9 were machined on carbons. Testing of these carbons was done in a NASA-MSC type carbon burner using a three-minute test duration per joint. Three joints of each design were tested. Arc sputtering rates measured in this test were as follows:

Joint #1 - 0.22 mg/min.
Joint #2 - 0.31 mg/min.
Joint #3 - 0.92 mg/min.

Visual inspection of the quartz plates after the test yielded the following observations:

(1) Joint #3 produced much more sputtering than joints #1 or #2.
(2) Quartz plates from tests on joints #1 and #2 appeared to have about the same amount of deposits.
(3) Sputtering from joint #1 was concentrated in a smaller area of the quartz plate than sputtering from joint #2.

Light measurements were made on the bare arc to determine the amount of fluctuation in center light intensity which occurs during the consumption of joints #1 and #2. Results of these measurements are illustrated in Figure 10. During the consumption of joint #1, the light intensity was depressed for a period of 37 seconds; for joint #2, this period was 18 seconds. The maximum depression of the light output for joint #2 was 10-12% and the light remained at this depressed level for a period of 7 seconds. Based upon the amount of sputtering and the light fluctuation during joint consumption, both joints #1 and #2 appear satisfactory.

Figure 11 illustrates fluctuation in the center light intensity which occurs during consumption of a truncated threaded joint with a flat face on the tang core and of a core nipple joint. Once again, the duration of light fluctuation during joint burn-through is less for the truncated thread joint.

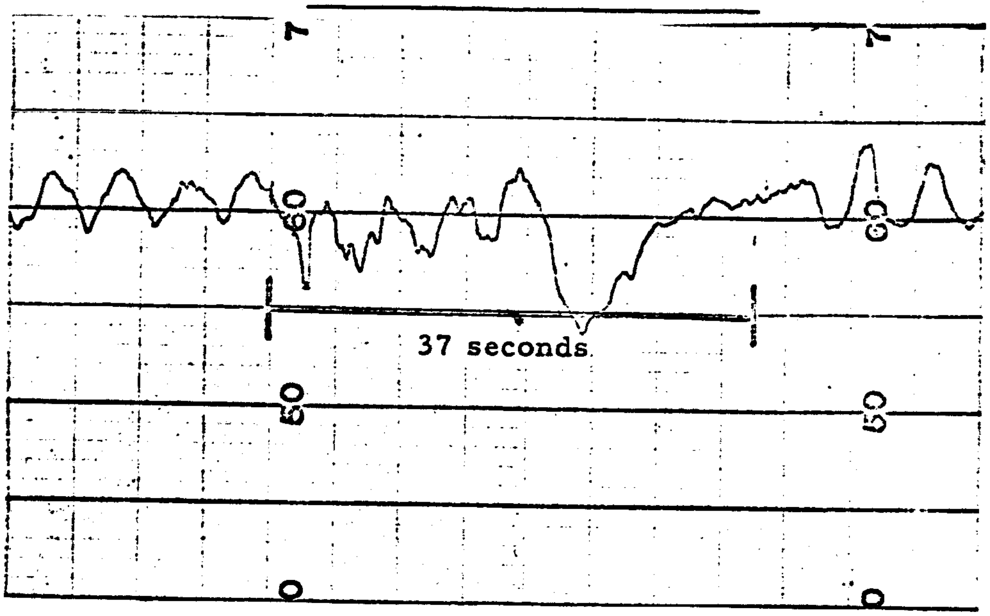
2.4 Choice of Best Joint Design

Data discussed in earlier sections of this report indicate that the two superior joint designs are the tapered conical joint of RCA and the 9/16-18 NS truncated threaded joint with the conical depression in the tang core. Of these two joints, the 9/16-18 threaded joint appears better than the conical joint for the following reasons:

FIGURE 10

Relative Center Light Fluctuation During Joint Burn Through

Joint #1
RCA Conical Threaded Joint



Joint #2
9/16"-18NS Truncated Thread With Conical Depression in Core of Tang

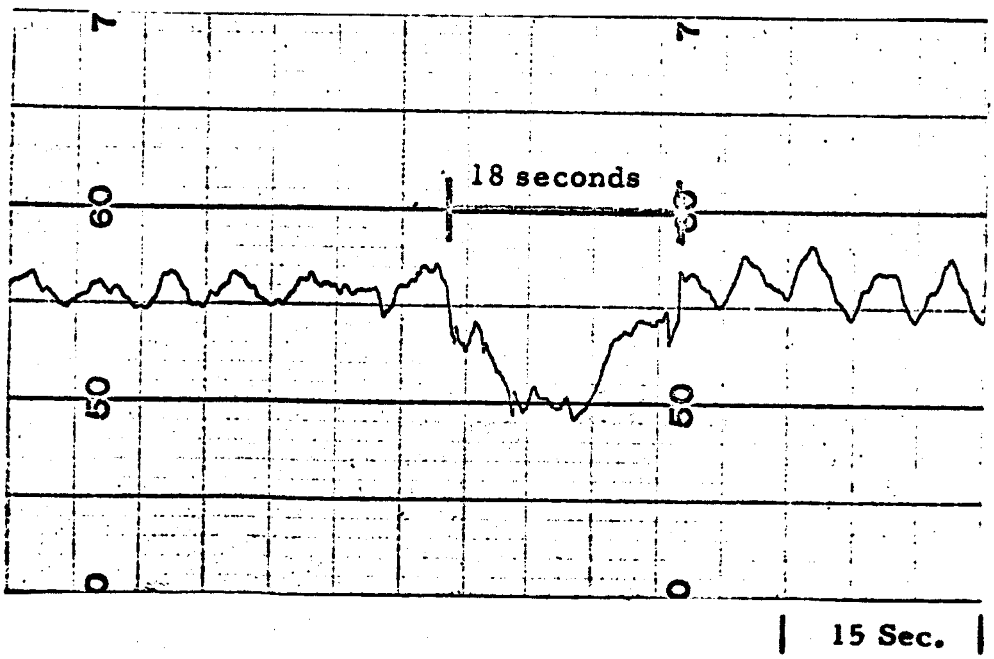
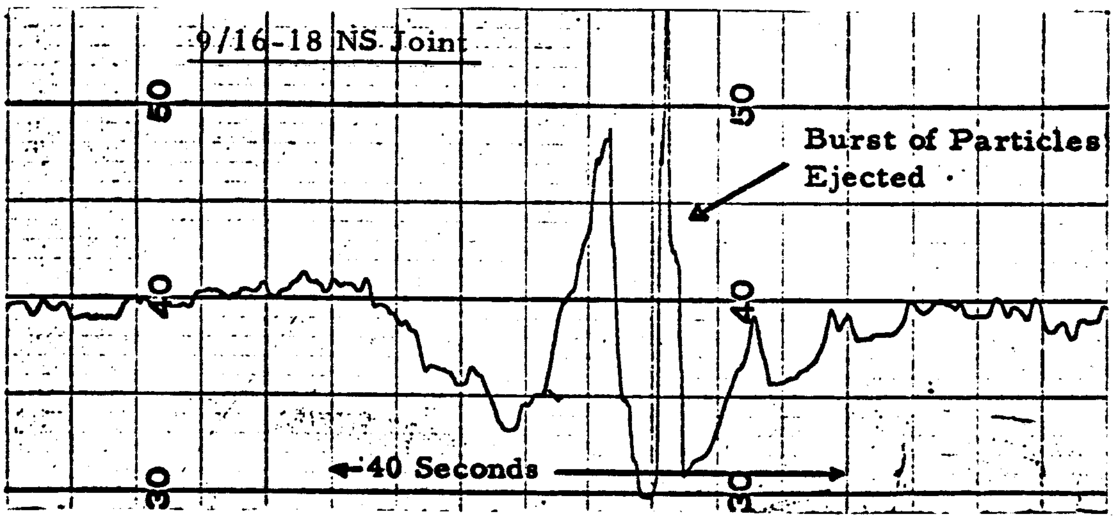
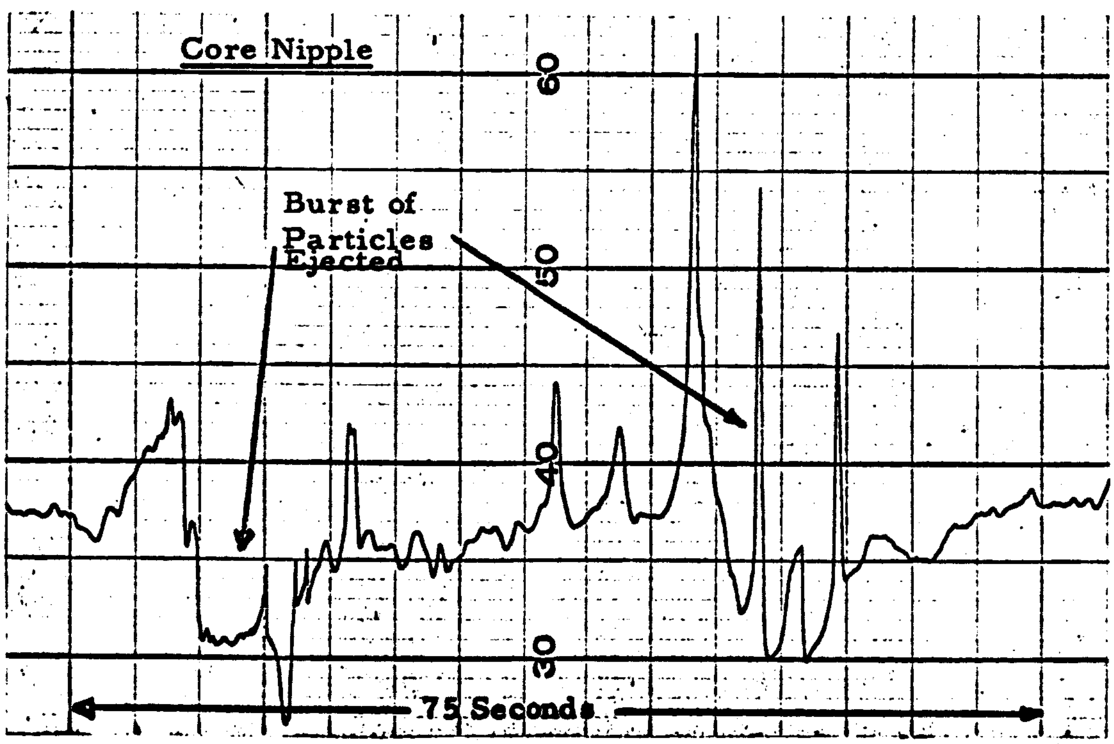


FIGURE 11

Relative Center Light for Core Nipple vs. that for 9/16-18 NS Threaded Joint





15 Sec.

(1) The sputtering of the two joints is comparable in magnitude, but the 9/16-18 NS joint will produce a more random pattern of particles upon elements of the optical train. This situation will produce a more uniform attenuation of intensity across the light beam, and will allow more meaningful adjustments to correct for the light attenuation.

(2) The duration of maximum light fluctuation is less when the 9/16-18 NS joint is consumed.

(3) The 9/16-18 NS joint has a higher mean strength and the spread of strength is less than that for the conical joint.

(4) Strength of the conical joint is a direct function of the adherence of the threaded section of the shell wall to the core. For maximum strength with the conical joint, 360° of circumferential adherence between shell and core on each end of each carbon is necessary. With the 9/16-18 NS joint, maximum strength can be achieved with as little as 300° of circumferential adherence between shell and core.

(5) Times required to machine a tang on one end and a socket on the other end of a carbon rod are 60 seconds for the conical joint and 32 seconds for the 9/16-18 NS threaded joint.

The cement designated as B in this report should be used to bond the shell to the core. It should be injected into the annular space between shell and core to a penetration of 2-3" and cured at 350°C. The reasons for choosing cement B are as follows:

(1) The cement B gives the greatest amount of dense residual material when cured to 350°C.

(2) Joint strength is higher on carbons bonded with cement B, than it is on carbons bonded with the best previous cement, cement A.

(3) Visual inspection of the bond between shell and core shows that cement B gives better adherence between shell and core than does cement A.

(4) No fouling of the contacts is anticipated with cement B cured at 350°C, since the mechanism of pyrolysis is similar to that of cement A, which resulted in no fouling after 12 hours of continuous burning.

(5) The 9/16-18 NS threaded joints machined on carbons bonded with B cement broke at an average torque of 240 in-oz with a lower 3-sigma value of 180 in-oz.

3.0 Arc Sputtering in Unjointed Electrode Sections

3.1 Possible Causes of Arc Sputtering

Arc sputtering is defined as the ejection of incandescent particles from a carbon electrode during arc operation with consequent pitting and opaquing of optical elements by these particles. The problem of minimizing arc sputtering during the consumption of unjoined electrode sections was accorded second priority under contract NAS 9-3699. Information available prior to the beginning of work under this contract indicated that the rate of arc sputtering for a particular carbon and burner system depended upon the burner design, the arc operating conditions and the carbon electrode composition. In this study, no experiments were done with the burner design and very few experiments were done with arc operating conditions. Attention was focused on the relationship of the electrode core composition to arc sputtering. The specific goal was to develop carbon electrodes which produce a minimum rate of arc sputtering and are least sensitive to changes in arc operating conditions.

3.2 Initial Measurements of Arc Sputtering

The development of a quantitative test for measuring the amount of arc sputtering was necessary for the study of this problem. A test which is referred to in this report as the quartz plate test was devised and found to be satisfactory for this purpose. In this test, particles ejected by arc sputtering strike and adhere to a quartz plate located about 3-1/2" in front of the arc. The rate of arc sputtering is determined by dividing the increase in weight of the plate measured in milligrams by the number of minutes the plate was exposed to the arc. The rate of arc sputtering was measured for standard commercially available solar carbons at the beginning of the contract period. These measurements were made to define the problem of arc sputtering and to provide a basis for evaluation of experimental core compositions. An MSC arc carbon burner located at RCA Service Company, Cherry Hill, New Jersey, was used for these tests which were made at 400 amps arc current. In testing unjoined electrode sections, the quartz plates were exposed to the arc for 20 minutes, then removed, cooled and packed in a polyethylene bag for subsequent weighing and inspection.

Three 16mm positive carbon electrodes were tested and found to have an average rate of sputtering of 1.4 milligrams per minute. The first two electrodes tested had an average rate of sputter of 0.8 milligrams per minute; the third electrode had a rate of sputter of 2.7 milligrams per minute. The third electrode was tested after 8 hours of continuous operation of the burner. After the burner had been shutdown, a thick black deposit was found on the positive contact. This deposit, which was caused by condensable materials from the pyrolysis of the epoxy-phenolic bonding resin used to cement the cores within the shells, probably increased in thickness as the test progressed. Thus, the heat transfer across the water-cooled contact-carbon interface undoubtedly decreased as the test progressed. At the beginning of the test, the positive contacts were cleaned, and it can be assumed that cooling of the positive carbon was at maximum effectiveness. The sputtering rate of 0.8 milligrams per minute obtained for the first two carbons tested under the more typical burner conditions can be regarded as average for the electrodes available at the time contract work on this problem was begun. The high sputtering rate of 2.7 milligrams per minute for the third electrode tested is not typical since it was probably caused in part by insufficient cooling of the carbon electrode resulting from the deposits between the electrode and the surface of the positive contacts. Prior experience has shown that poor cooling does increase the rate of arc sputtering.

3.3 Effect of Core Composition Upon Arc Sputtering

A series of experiments was conducted to determine the effect of the positive electrode core composition upon arc sputtering. Cores for these experiments were made from core blends having different compositions, by mixing the blends with a pitch binder, extruding the mixture, and baking the formed cores in a reducing atmosphere to a temperature of 1000°C. Testing of the cores was done by assembling them into carbon shells and burning the resulting electrodes in a MSC arc carbon burner at 400 amps. The rate of arc sputtering for each core composition was measured by the quartz plate test.

The core composition which was being used for solar carbons at the time this study began had a rare earth fluoride (REF) to rare earth oxide (REO) ratio of approximately 1:1 and a graphite to total rare earth (REF + REO) ratio of 1:1. This core composition is shown in Table 13.

TABLE 13

Composition of 16mm Solar Carbon Core Blend at Beginning of Contract Study

Material	Percent by Weight
Rare earth fluoride (REF)	20
Rare earth oxide (REO)	23
Graphite, natural flake	44
Strontium fluoride	10
Sulfur	3

The binder for the core blend composition shown in Table 13 was a coal tar pitch, which was added to the blend in the weight ratio of 17 pts. pitch to 100 pts. blend.

In initial experiments made to determine the effect of core composition upon arc sputtering, both the ratio of REF to REO and the ratio of graphite to total rare earths (REF + REO) were varied over a wide range. The compositions of seven different cores made during these experiments, and the results of arc sputtering tests on the cores are given in Table 14.

TABLE 14

Arc Sputtering Tests on Solar Carbons Having Experimental Cores

Core No.	Composition, Weight Ratio** REF:REO	Graphite: (REF+REO)	Arc Sputtering Rate, mg/min.	Total Test Time, min.
1	3:1	1:1	0.20	34
2	1:3	1:1	-	-
3	3:1	3:1	<0.002*	40
4	1:3	3:1	<0.004*	40
5	1:1	3:1	<0.004*	40
6	1:1	1:1	0.20	40
7	1:1	1:1	0.26	45

* Actual quantity too small to be weighed. Amounts estimated by visual inspection and comparison with plates sufficiently loaded to permit weighing.

** REF is rare earth fluoride; REO is rare earth oxide.

The ratio of REF:REO shown in Table 14 is calculated from the percent by weight of REF and REO in the core blend. The ratio of graphite to (REF+REO) is calculated from the percent by weight of graphite and (REF + REO) in the core blend.[1] In all seven of the core compositions given in Table 14, the

[1] In the monthly progress reports issued under this contract, the ratio of graphite to REF+REO was calculated on the basis of the percent by weight of graphite in the standard core (i.e. 44% from Table 13) divided by the percent by weight of REF+REO in the experimental core, with no allowance made for the fact that each percentage decrease in total rare earth content was accompanied by an equivalent percentage increase in graphite content. These ratios of graphite to REF+REO which were reported incorrectly appear in the following progress reports: No. 3, p. 4; No. 4, p. 6; No. 5, p. 4. In this report, these errors have been corrected and reported along with a more detailed description of core composition.

percentages of strontium fluoride and sulfur were constant at 10% and 3%, respectively. Thus the total percentage of graphite, REF and REO used in all of the compositions was constant at 87%. Core #7 was selected as the basis for judging the relative rate of arc sputtering of the different core compositions since it was made from the composition given in Table 13 which was in use at the beginning of the contract study.

Preliminary quartz plate tests for arc sputtering were made in a Mole-Richardson test lamp on carbons with cores #1, 2, 3 and 4. Results of the preliminary tests showed that core #2 sputtered very badly and it was not tested further since sputtering is known to be more pronounced in the MSC burner than in the Mole-Richardson lamp. Cores #3 and 4, which had a substantially lower rare earth content than standard solar carbon cores, burned very quietly with much less sputter than did core #1 or core #7. Carbons made with cores #3 and 4, however, burned about 25% slower and had 30% lower light output than standard solar carbons (core #7) tested at the same current, 400 amps.

After the preliminary tests, carbons made from cores #1 and cores #3 through 7 were tested in a MSC burner. The arc sputtering rates shown in Table 14 were determined by the quartz plate test which has been described earlier. These test results indicate that cores having a low rare earth content (cores #3, 4 and 5) sputter at a materially reduced rate. Although light output was not measured in these tests, the preliminary tests had shown that it was low for carbons with low rare earth content.

Core #6 was made from graphite which had been purified to reduce its ash content to less than 0.01%. This experiment was performed to determine whether the ash (especially iron compound) in the graphite was causing or contributing to arc sputtering. Cores #6 and 7 are alike excepting that core #7 was made from standard commercial graphite which was not purified. Since little difference exists in the arc sputtering rates for cores #6 and #7, ash in the graphite does not appear to cause arc sputtering.

At this point in the program, experimental results had shown that: (1) the rate of arc sputtering could be reduced substantially by reducing the rare earth content of the carbon core and (2) this reduction in rare earth content of the core caused a reduction in the burning rate of the carbon and a large reduction in light output. A series of experimental cores with different compositions was prepared to obtain additional information about the dependance of both arc sputtering and light output on the rare earth content in the core. The composition of these cores and the performance in an MSC burner of carbons made from these cores are shown in Table 15. All of the tests were made at 400 amps arc current and the arc power was determined by

TABLE 15

Arc Sputtering Tests on Solar Carbons Having Experimental Cores

Core No.	Composition, Weight Ratio** REF:REO	Composition, Weight Ratio** Graphite: (REF + REO)	Arc Sputtering Rate, mg/min.	Light Output Relative Center Brightness	Carbon Consumption in./hr.	Arc Power, KW	Total Test Time, mins.
7	1:1	1:1	0.26	100	58.2	31.2	45
8	1:1	2:1	<0.004*	90.5	48.3	28.8	20
9	1:2	2:1	<0.004*	87.0	46.3	28.4	20
10	1:1	1.5:1	<0.025*	95.5	51.7	28.4	20
11	1:2	1.5:1	<0.017*	95.5	50.9	29.6	80
12	2:1	1.5:1	<0.025*	94.0	51.1	29.2	20
13	1:1	1.2:1	0.075	not measured	53.5	30.0	20
14	2:1	1.2:1	0.10	not measured	53.5	29.6	20

* Actual quantity too small to be weighed. Amounts estimated by visual inspection and comparison with plates sufficiently loaded to permit weighing.

** REF is rare earth fluoride; REO is rare earth oxide.

the arc voltage which differed for the various carbons. Core #7 was again selected as the basis for judging the performance of the other cores. Arc sputtering rates were measured by the quartz plate test. Based upon the results shown in Table 15, the performance of carbons containing core #11 most nearly approximates the objective of high light output and minimum arc sputtering.

Data from Table 15 showing the relationship of the rare earth content of the core to the light ouput and amount of arc sputtering is presented graphically in Figure 12. In this figure, core #7 is taken as the basis for comparison and is assigned the relative value of 100% for both light output and arc sputtering. Figure 12 shows that as the total rare earth content of the core is decreased below the 44% rare earth level contained in core #7, light output decreases slowly but arc sputtering decreases at a very rapid rate.

3.4 Performance Tests on Best Electrode Composition

About 25 pieces of 16mm solar carbons containing core #11, the best core composition selected from among those in Table 15, were sent to RCA Service Company for testing. The tests to be made included measurement of light output of these carbons in a NASA MSC burner equipped with optics. In a telephone report on the outcome of these tests, an RCA engineer stated that these carbons had the least amount of arc sputtering of any carbons they had received to date.[1] Light output was reported to be 8% below that of control carbons (containing core #7) but was sufficient to meet specifications. Although spectral energy distribution has not been measured on the new cores by UCC, measurements made at RCA show no difference in the energy distribution because of the reduction in rare earth content of the core.[2]

4.0 Limited Production Run of Best Electrode Composition

As agreed in contract NAS 9-3699, a limited production run of 700 pieces of 16mm by 30-inch solar positive carbons incorporating all improvements made during the term of the contract has been processed and will be supplied to the NASA Manned Space Center. Process flow diagrams showing the manufacturing operations involved in making solar carbons are presented in Figures 13, 14, and 15. This lot of carbons represents the contractor's best efforts and includes the following improvements over carbons available prior to the contract study:

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[1] Telephone conversation with Mr. R. D. Kelley on April 26, 1965.

[2] Spectral data obtained from RCA on May 19, 1965.

FIGURE 12

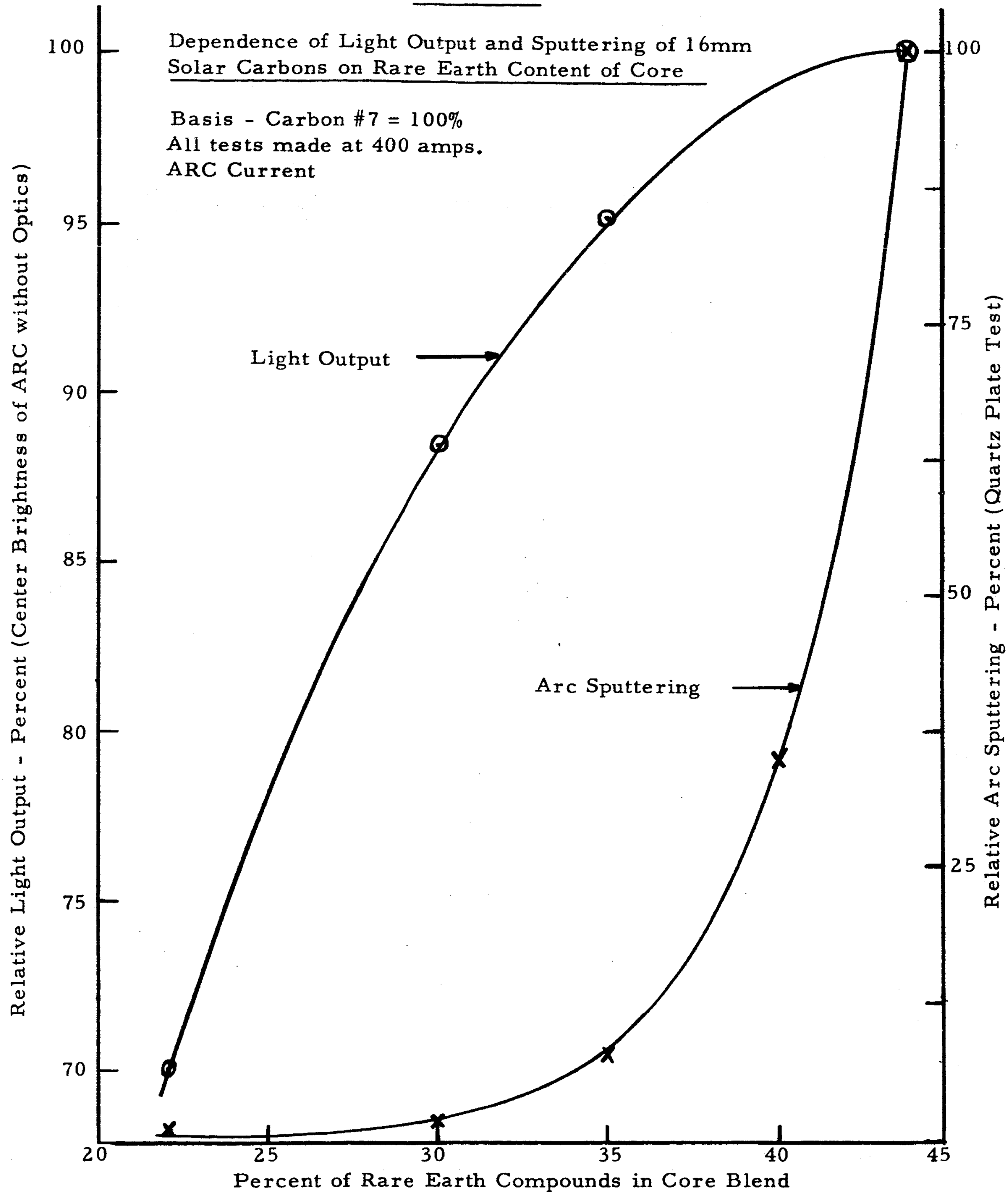

Dependence of Light Output and Sputtering of 16mm Solar Carbons on Rare Earth Content of Core
Basis - Carbon #7 = 100%
All tests made at 400 amps.
ARC Current
Light Output
Arc Sputtering
Relative Light Output - Percent (Center Brightness of ARC without Optics)
Relative Arc Sputtering - Percent (Quartz Plate Test)
Percent of Rare Earth Compounds in Core Blend
100
95
90
85
80
75
70
100
75
50
25
20
25
30
35
40
45

FIGURE 13

Process Flow Diagram for 16mm Solar Carbon Shells

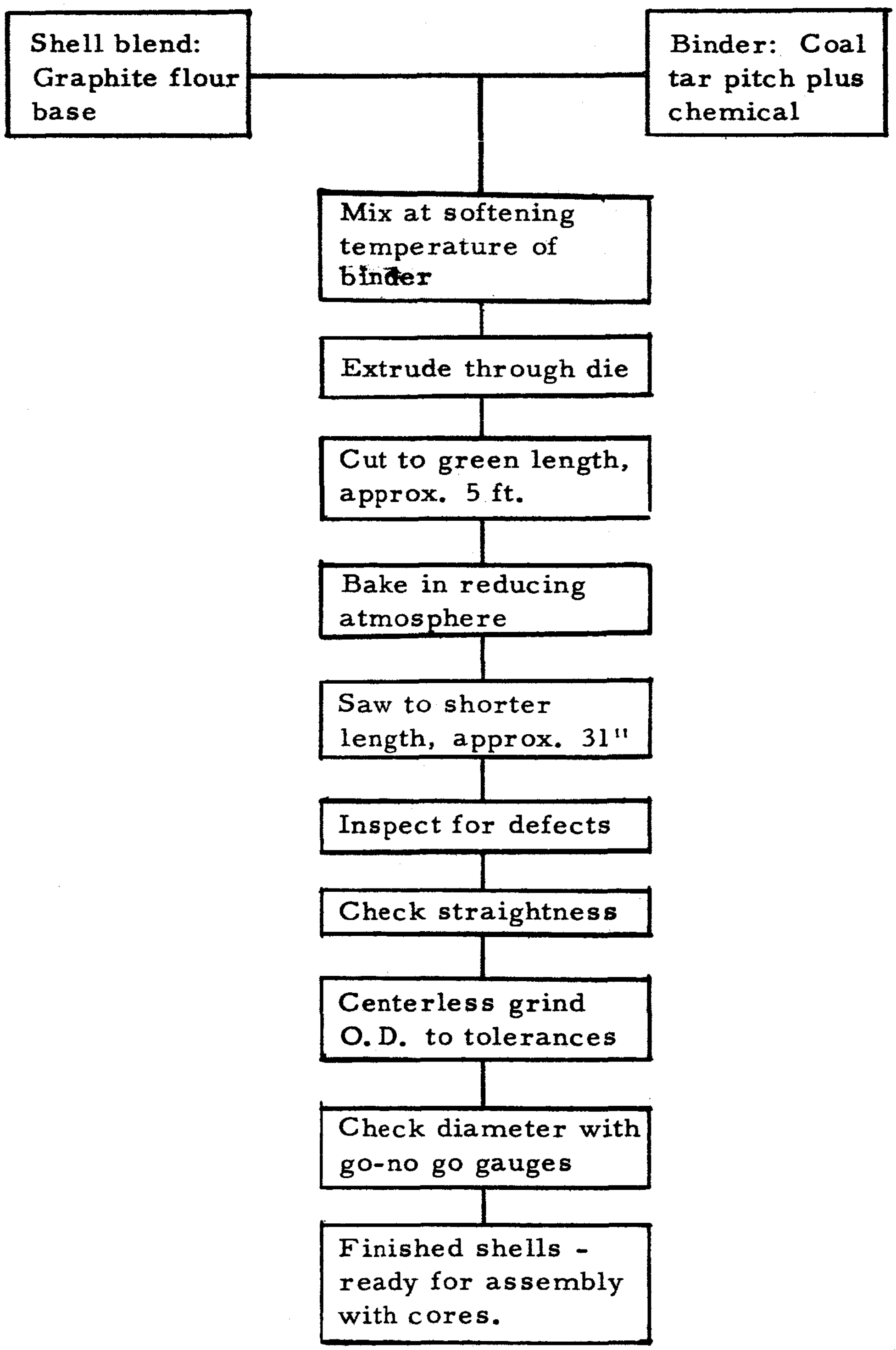


FIGURE 14

Process Flow Diagram for 16mm Solar Carbon Cores

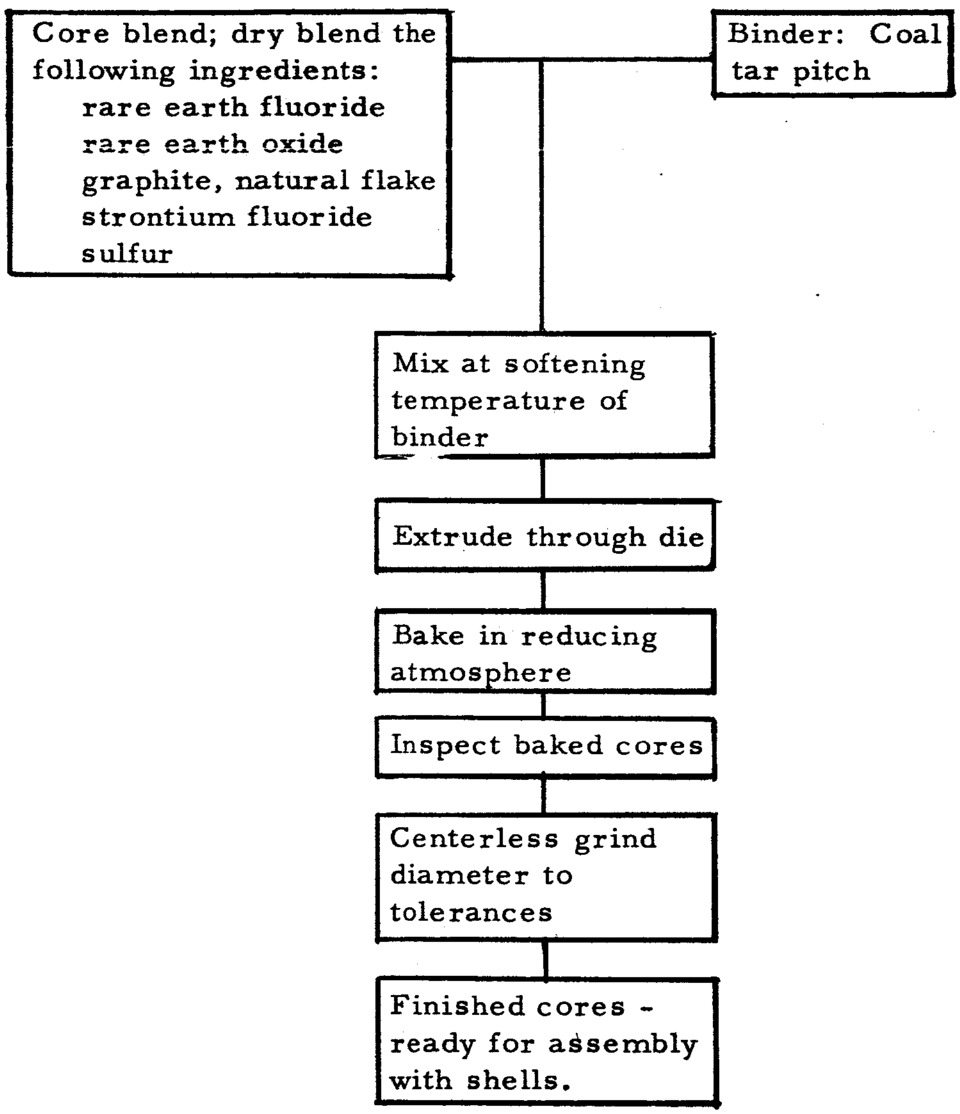
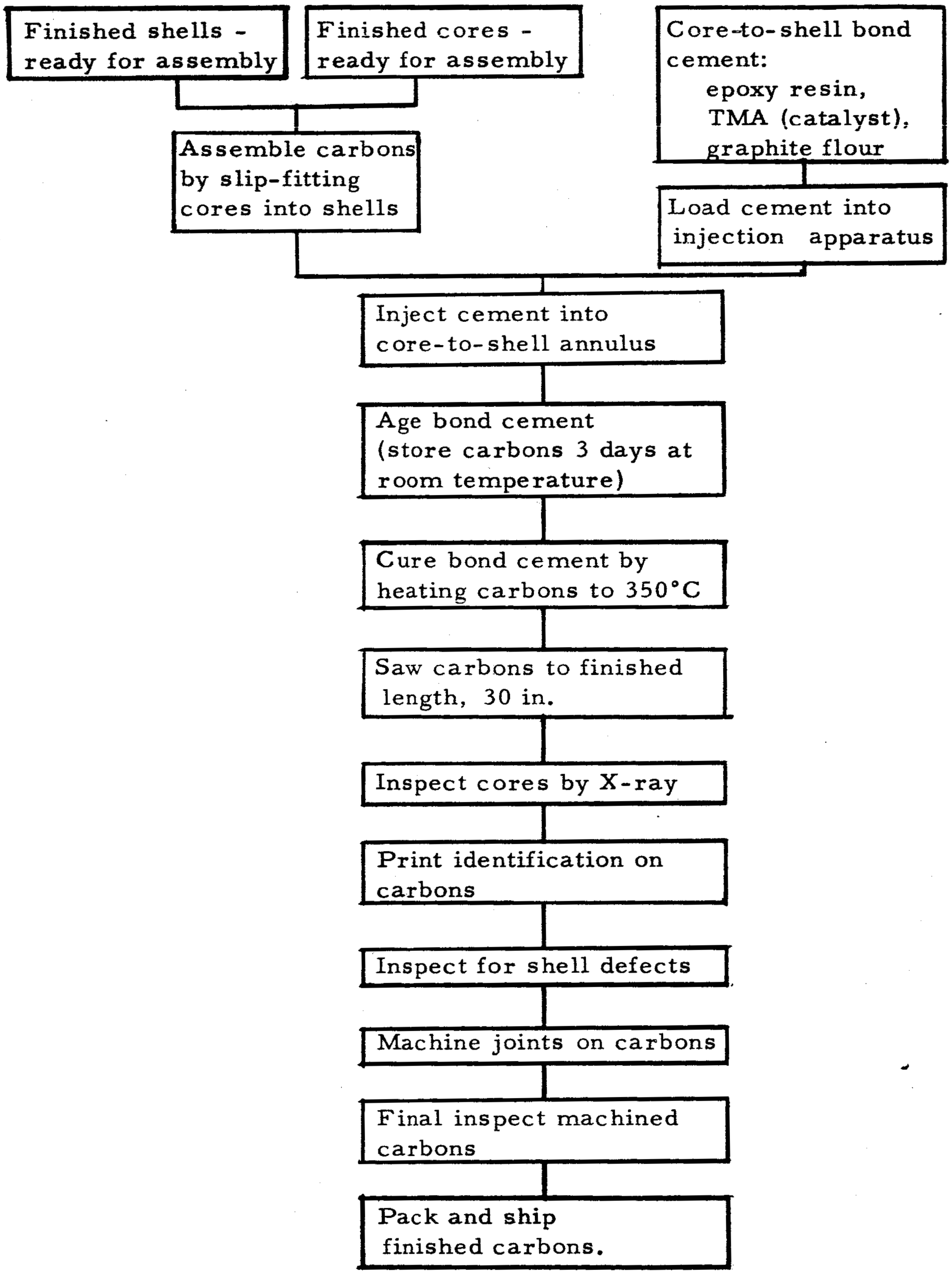


FIGURE 15

Process Flow Diagram for Assembly and Finishing of 16mm Solar Carbons



(1) The strength of carbon joints has been made higher and more uniform. This increased joint strength has been attained by several changes, namely

(a) Carbon shells have been made with protruding ribs on their I. D. The ribs center the core, permitting the bond cement to flow into the entire 360° of the annular space.

(b) A high strength core-to-shell bonding cement consisting of a catalyzed epoxy resin has been used.

(c) An optimum curing temperature - 350°C - has been used for the bond cement.

(d) A cement injection apparatus has been used to apply the core-to-shell bond cement. This procedure insures filling the annular space at the ends of the carbons with cement.

(e) A new joint design which employs a 9/16"-18NS truncated thread machined entirely within the shell wall has been adopted. Arc sputtering, formerly a problem with joints of this design, has been reduced substantially by machining a conical depression in the core of the tang.

(2) Arc sputtering during the consumption of unjoined electrode sections has been reduced substantially. This has been accomplished by a change in the core composition whereby the total percentage of rare earth fluoride (REF) and rare earth oxide (REO) has been reduced from 44% to 35% and the ratio of REF/REO has been reduced from 1:1 to 1:2.

5.0 Conclusions and Recommendations

Carbon joints which will withstand increased torque have been developed from work performed under this contract. Prior to the contract work, truncated thread joints of the best known design had a mean strength of 175 in.-oz. and a lower 3-sigma limit of 126 in.-oz. Development of a stronger core-to-shell bond permitted a change in the joint dimensions which increased the mean strength to 240 in.-oz. and the lower 3-sigma limit to 180 in.-oz. This is an increase of 35% in the mean strength and 40% in the lower 3-sigma limit of the strength.

Conical joints machined on carbons available prior to the contract work often exceeded the 175 in.-oz. strength of truncated thread joints, but the conical joints varied widely in strength because of the nature of the core-to-shell bond. Carbons developed under this contract are made with a new, higher strength core-to-shell bond cement. This cement is distributed uniformly within the core-to-shell annulus at the ends of the carbons by a method that is suitable for production operations. The strong bond provided by the new cement is expected to increase strength and reliability of conical joints as well as the truncated thread joints.

Arc sputtering during the consumption of truncated thread joints can be reduced substantially by making a conical depression in the core on the tang end of the carbon. Sample carbons having this new joint design have been supplied to the Manned Space Center.

A reduction in the amount of arc sputtering which occurs during the operation of an MSC solar simulator has been achieved by the development of a new electrode core formulation. Tests made in an MSC carbon burner have shown that the rate of arc sputtering for carbons having the new core is less by a factory of at least 15, perhaps as much as 30, compared with the best carbons available prior to the contract work. Production quantities of carbon electrodes having the new core formulation can be made on the basis of work completed under this contract.

Manufacture of a limited production run of 700 pieces of 16mm carbon electrodes for the Manned Space Center has been completed. These electrodes were made from the best formulation and by the best processing techniques known at the end of the contract period. Fifty of these improved electrodes have been shipped to the Manned Space Center and the remaining 650 pieces will be shipped about the end of June.[1]

[1] This date was agreed upon by E. L. Piper and J. P. Vincent in a telephone conversation on May 24, 1965.

On the basis of the contract work, the Carbon Products Division recommends that the following actions be taken:

1. Carbon electrodes made from the formulations and by the processing methods developed under this contract should be used in the NASA-MSC carbon burners.

2. A lead time of 10-12 weeks should be allowed for delivery on sizeable orders for solar carbon electrodes. This lead time is necessary because of the large number of processing operations involved in manufacturing solar carbons.

3. Development work should be continued to make further improvements in the performance of 16mm solar carbon electrodes. Only problems which were at the top of the priority list could be solved within the time and manpower limitations of contract No. NAS 9-3699. Among the goals proposed for this continued work are: (a) further reduction or elimination of arc sputtering, (b) elimination of material accumulation on simulator components, (c) increased proportion of radiation in the ultraviolet region of the spectrum, and (d) measurement of spectral energy distribution. A proposal for a contract to continue development work on the foregoing problems was submitted to the Manned Space Center of March 19, 1965.